

LOW TEMPERATURE OPERATION OF A SWITCHING POWER CONVERTER

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Abstract

The low temperature operation of a 48 W, 50 kHz, 36/12 V pulse width modulated (PWM) buck de-de power converter designed with standard commercially available components and devices is reported. The efficiency of the converter increased from 85.6% at room temperature (300K) to 92.0% at liquid nitrogen temperature (77 K). The variation of power MOSFET, diode rectifier, and output filter inductor loss with temperature is discussed. Relevant current, voltage, and power waveforms are also included.

Introduction

With the recent development of high temperature superconducting materials with a critical temperature of approximately 125K, it is foreseeable that superconducting and low temperature electronics will find applications in future power transmission and motor-generator systems. Applications of low temperature electronics include cryogenic instrumentation, medical diagnostics, superconducting magnetic energy storage systems, and high speed computer, communication and electronic systems [1,2].

One particular application of interest to aerospace industries is in deep-space exploration programs. Typical passive spacecraft temperature varies from 448K in Mercury and gradually drops to 44K in Pluto. The current practice is to use radio-isotope thermoelectric generators (RTGs) and radio-isotope heating units (RHUs) to shield the electronic circuitry from low temperatures of deep space. In addition to the fact that RTGs and RHUs are expensive and environmentally unfriendly, RHUs are always on and therefore require additional heat rejection system when the space probe is near the earth orbit.

If electronic circuits can be designed to operate from room temperature down to a very low temperature (e.g., liquid nitrogen temperature of 77K), then the use of RTGs and RHUs will not be required. Additionally, launch weight and cost will be significantly reduced due to the absence of any heat rejection and thermal shielding systems for electronics.

The objective of this research was to investigate the possibility of designing and operating basic power processing electronics suitable for operation from 300K down to 77K using standard commercially available components. For this purpose, a 48 W, 36±6/12 V, 50 kHz pulse-width modulated (PWM) de-de power converter was designed and tested in the laboratory at 300K and 77K. Its efficiency increased from 85.6% at 300K to 92% at 77K. The converter performance, component loss, and relevant waveforms are discussed in the following sections.

PWM Buck converter

The 48 W, 36±6/12 V, 50 kHz PWM buck converter was designed for operation at 300K as well as at 77K. This type of power converter can potentially be used in small scientific/experimental spacecraft such as the proposed

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CLIR (Combined Lander and Instrumented Rover). The basic converter circuit is shown in Fig. 1. It was designed for a minimum load current of 1 A for continuous conduction mode of operation and a maximum output voltage peak-to-peak ripple of 1%.

Based on the steady-state analysis for continuous conduction mode of operation of a PWM buck converter [3], the following design equations are used for the power circuit design:

$$L_f \geq \frac{V_o(1 - D_{min})}{2f_s I_{o,min}} \quad (1)$$

$$C_f \geq \frac{(1 - D_{min})V_o}{8L_f f_s^2 (\Delta V_o)} \quad (2)$$

where, D_{min} = minimum duty ratio $\equiv V_o/V_{in,max}$, $I_{o,min}$ = minimum output (load) current for continuous conduction mode of operation, f_s = switching frequency, and ΔV_o = peak-to-peak output ripple voltage.

Based on equation (1), the required filter inductance is 85.7 μ H and was designed using a distributed air gap ferrous alloy powder core from Magnetics (KoolM μ 77934) with a relative permeability of 90. Standard magnet wire (3*#20 AWG) was used for winding 27 turns on the core to obtain the desired filter inductance. Based on previously reported work with molypermalloy powder cores [4], it was expected that the designed inductor will work at low temperature even though its loss might increase a little [5,6].

The required filter capacitance was found to be 41.7 μ F using equation (2). For the power converter an output filter capacitance of 50 μ F was used. Standard metallized polypropylene film capacitors were used because of their superior low temperature characteristics [7].

Power semiconductor selection: For low temperatures, the primary semiconductor material is silicon, although gallium-arsenide also has considerable potential and the primary device is the field-effect transistor in various forms [1,2,8]. Reduced temperature operation offers improvements in performance through improvement of material-based properties such as electronic carrier mobility, thermal conductivity, and electrical conductivity. For this work, standard plastic packaged (TO-220) IRF-540 power MOSFET (28 A, 100 V, 85 m Ω , 560 pF device) was used as the controllable power switch and a MBR-20100CT (20 A, 100 V, V_F = 0.9 V) Schottky diode was used as the output rectifier.

Experimental procedure and results:

The complete power converter tested at room and liquid nitrogen temperature is shown in Fig. 2. The open-loop control circuit was designed around a bicmos voltage-mode PWM IC (TC35C25CPE) and a CMOS driver IC (IR-2113). The programmed switching frequency was 50 kHz, and the duty ratio was controllable through the 20 k Ω potentiometer kept at room temperature. The driver IC has independent high and low-side referenced output channels. The high-side floating channel was used to drive the power MOSFET without having to use an optocoupler or an isolation transformer. The resistors used in the control circuit were metal-film type and the capacitors were NPO ceramic type, both having fairly temperature independent characteristics [7].

The full-load data were recorded both at 300K and 77K. The control and power circuitry were placed inside a Dewar flask whereas the measuring and sensing instruments were at room temperature, resulting in a highly non-compact circuit layout. The power converter was capable of restarting at 77K. Recorded results and waveforms are discussed next.

The full-load efficiency of the converter increased from 85.6% at 300K to 92% at 77K, and the converter loss decreased from 6.9 W at 300K to 3.6 W at 77K. The switch loss was less than a watt at both temperatures. The filter inductor loss was about two watts and increased slightly at 77K compared to 300K, primarily due to increased

flux density and decreased core resistivity [5,6]. The rest of the loss was due to the output rectifier, output filter capacitor, and stray losses in long cables used for testing the circuit immersed in liquid nitrogen. The stray loss decreased significantly at 77K compared to 300K, primarily due to improved electrical conductivity of wires.

Figures 3, 4, and 5 show the voltage, current, and power waveforms of switch, diode, and inductor, respectively, for 77K and 300K operation. The voltage waveforms show a significant amount of high frequency ringing during the switch turn-on and turn-off instants. This is inherent in any hard-switched converter because instantaneous change in voltage and current is opposed by the switch capacitance and circuit layout inductance, respectively. The high frequency ringing is caused by resonance between the switch and Schottky rectifier capacitance and the circuit layout inductance [5]. The circuit layout inductance was significant due to the experimental setup where the converter circuit was immersed in a liquid nitrogen filled Dewar whereas all the measuring instruments were outside the Dewar. This is evident in Figs. 3 and 4, because the turn-off ringing is much more significant than the turn-on ringing. It can also be noticed that the waveforms at 77K and 300K look almost identical except for the fact that the switching noise is somewhat less at 77K.

Finally, the switching frequency of the converter changed from 51.3 kHz at 300K to 49.7 kHz at 77K, indicating an overall change of only 3%. This change is primarily contributed by the external timing resistor and capacitor used for programming the switching frequency of the PWM control IC. The monolithic resistors and capacitors internal to the PWM IC also play an important role. However, a minor variation in switching frequency will not be a problem for most switching power converters.

Conclusions

This work demonstrated the possibility of successfully operating a power electronic converter from room temperature down to the liquid nitrogen temperature, designed with standard commercially available components and devices. The efficiency of the converter increased from 86.6% at 300K to 92% at 77K. The switching frequency decreased by 3% at 77K respect to 300K operation. The semiconductor and passive component loss as a function of temperature must be looked at further details. The electronic packaging and related thermal mismatch issues must be investigated before any low temperature use of electronics is contemplated.

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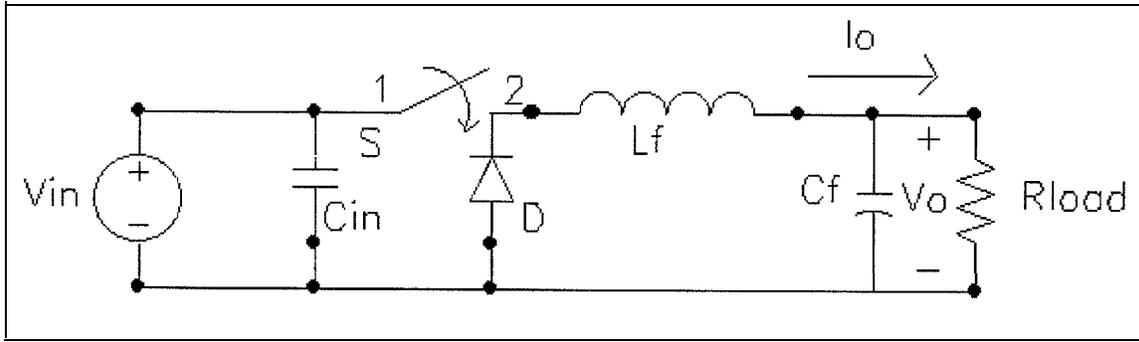


Figure 1 PWM buck dc-dc converter.

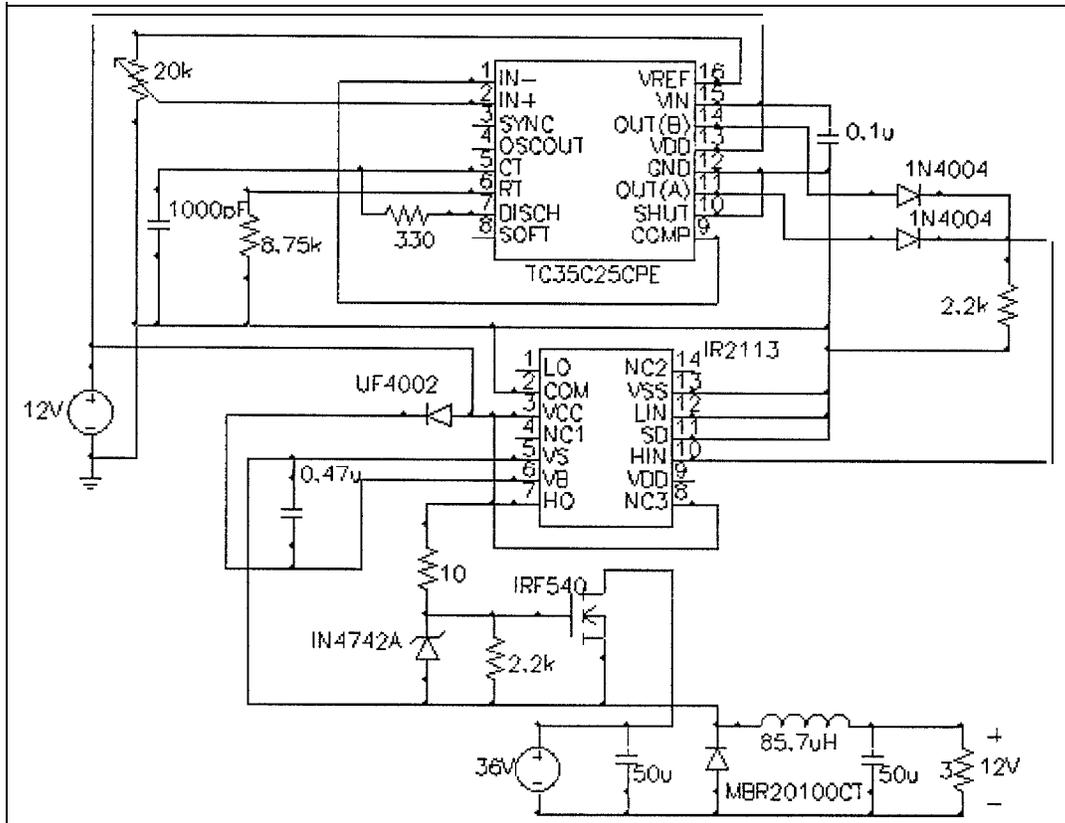
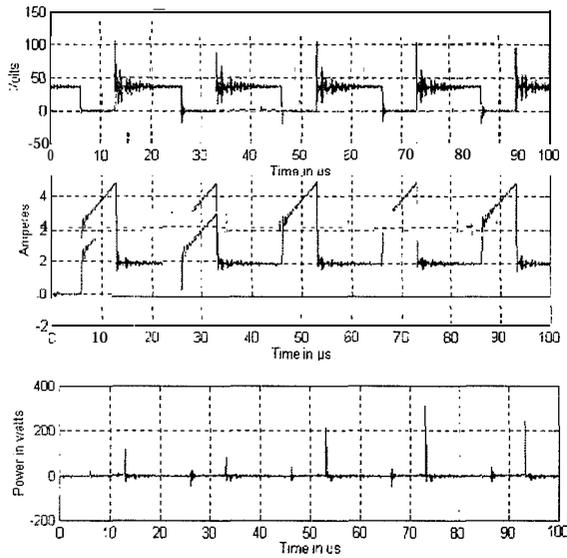
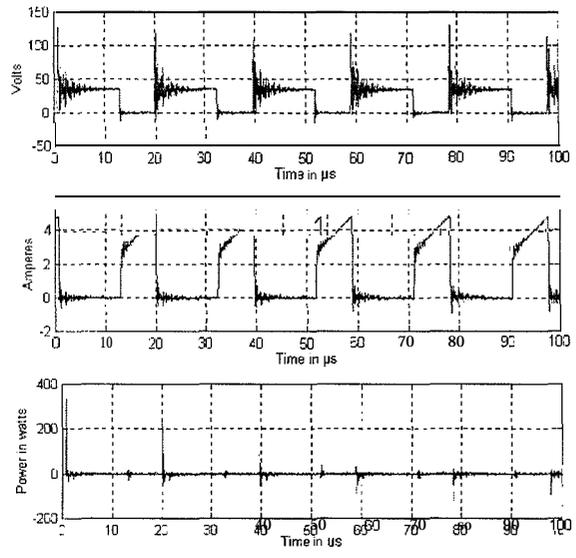


Figure 2 Complete converter circuit tested at 300K and 77K.

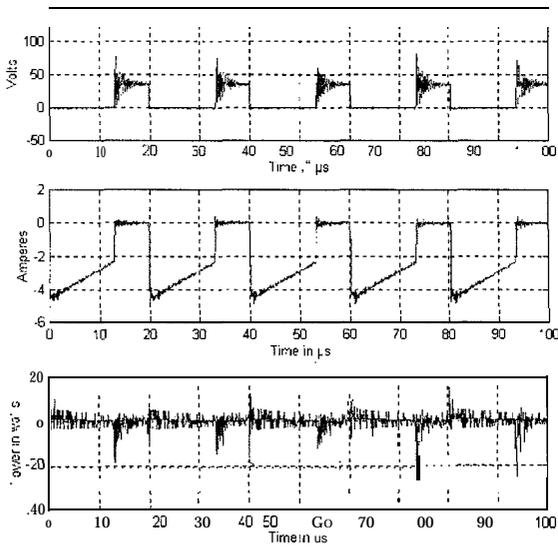


(a) 77K operation

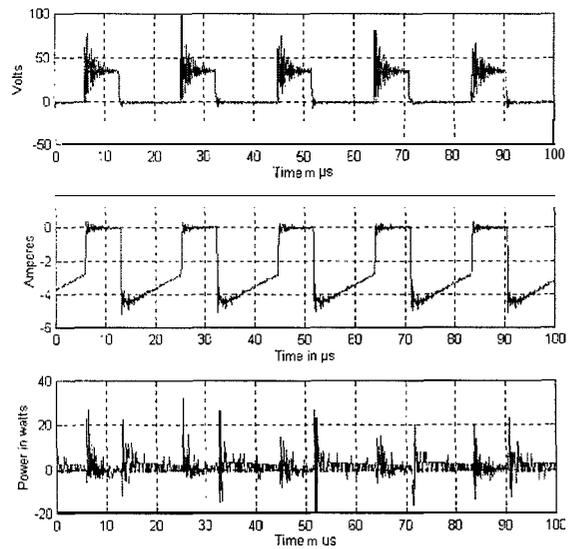


(b) 300K operation

Fig. 3 Switch voltage, current, and power waveforms.

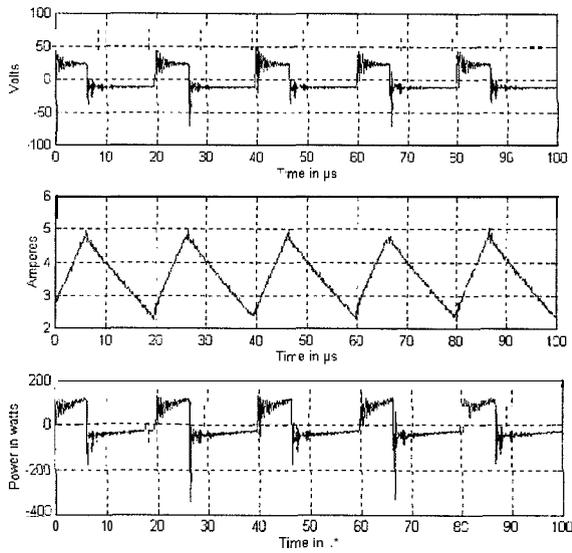


(a) 77K operation

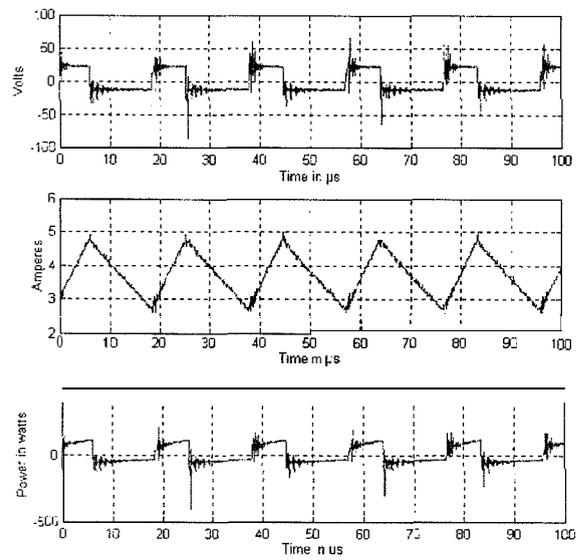


(b) 300K operation

Fig.4 Diode voltage, current, and power waveforms.



(a) 77K operation



(b) 300K operation

Fig. 5 Inductor voltage, current, and power waveforms.